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J. W. Harris and the STAR Collaboration

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ABSTRACT

An overview of the STAR experiment at the Relativistic Heavy Ion Collider is presented. The experiment will concentrate on the measurement of particle production and jet production at midrapidity in a search for the Quark-Gluon Plasma. These hadronic observables will be studied on an event-by-event basis to determine the thermodynamics of single events and to identify special and unusual events. The physics addressed by STAR is discussed.

1. Introduction to the STAR Experiment

Lattice QCD predictions[1] exhibit a phase transition from hadronic matter to a plasma of deconfined quarks and gluons, called the Quark-Gluon Plasma (QGP), at a temperature near 250 MeV. This phase of matter must have existed shortly after the Big Bang and may exist in the cores of dense stars. An important question is whether this predicted state of matter can be created and studied in the laboratory.

The STAR (Solenoidal Tracker At RHIC) experiment will search for signatures of Quark-Gluon Plasma (QGP) formation and investigate the behavior of strongly interacting matter at high energy density. Since there is no single accepted signature for the QGP, it is essential to use a flexible detection system at the Relativistic Heavy Ion Collider (RHIC)[2] that can simultaneously measure many experimental observables. The experiment will utilize two aspects of hadron production that are fundamentally new at RHIC: correlations between *global observables on an event-by-event basis* and the use of *hard scattering of partons* as a probe of the properties of high density nuclear matter. The event-by-event measurement of global observables – such as temperature, flavor composition, collision geometry, reaction dynamics, and energy or entropy density fluctuations – is possible because of the very high charged particle densities, $dn_{ch}/d\eta \approx 1000$ expected in nucleus-nucleus collisions at RHIC. This will allow novel determination of the thermodynamic properties of single events. Full azimuthal coverage with good particle identification and continuous tracking is required to perform these measurements. Measurable jet yields at RHIC will allow investigations of hard QCD processes via both highly segmented calorimetry and high p_t single particle measurements. A systematic study of particle and jet production will be carried out over a range of colliding nuclei from p + p through Au + Au, over a range of impact parameters from peripheral to central, and over the range of energies available at RHIC. Correlations between observables will be made on an event-by-event basis to isolate potentially interesting event types. Measurements of the remnants of hard-scattered partons will be used as a penetrating probe of the QGP, and will provide important new information on the nucleon structure function and parton shadowing in nuclei.

Measurements will be made at midrapidity over a large pseudo-rapidity range ($|\eta| < 2$) with full azimuthal coverage ($\Delta\phi = 2\pi$) and azimuthal symmetry. The detection system is shown in Fig. 1. It will consist of a silicon vertex tracker (SVT) and time projection chamber (TPC) inside a superconducting solenoidal magnet for tracking, momentum analysis and low p_t particle identification via dE/dx; a time-of-flight system surrounding the TPC for particle identification at higher momenta; and electromagnetic calorimetry outside the solenoid to trigger on and measure jets, and to measure the transverse energy of events. The tracking and particle identification are needed mainly to study the low p_t physics, and the calorimetry to study the high p_t physics. Details of the various detector systems and the experiment are described elsewhere.[3,4]

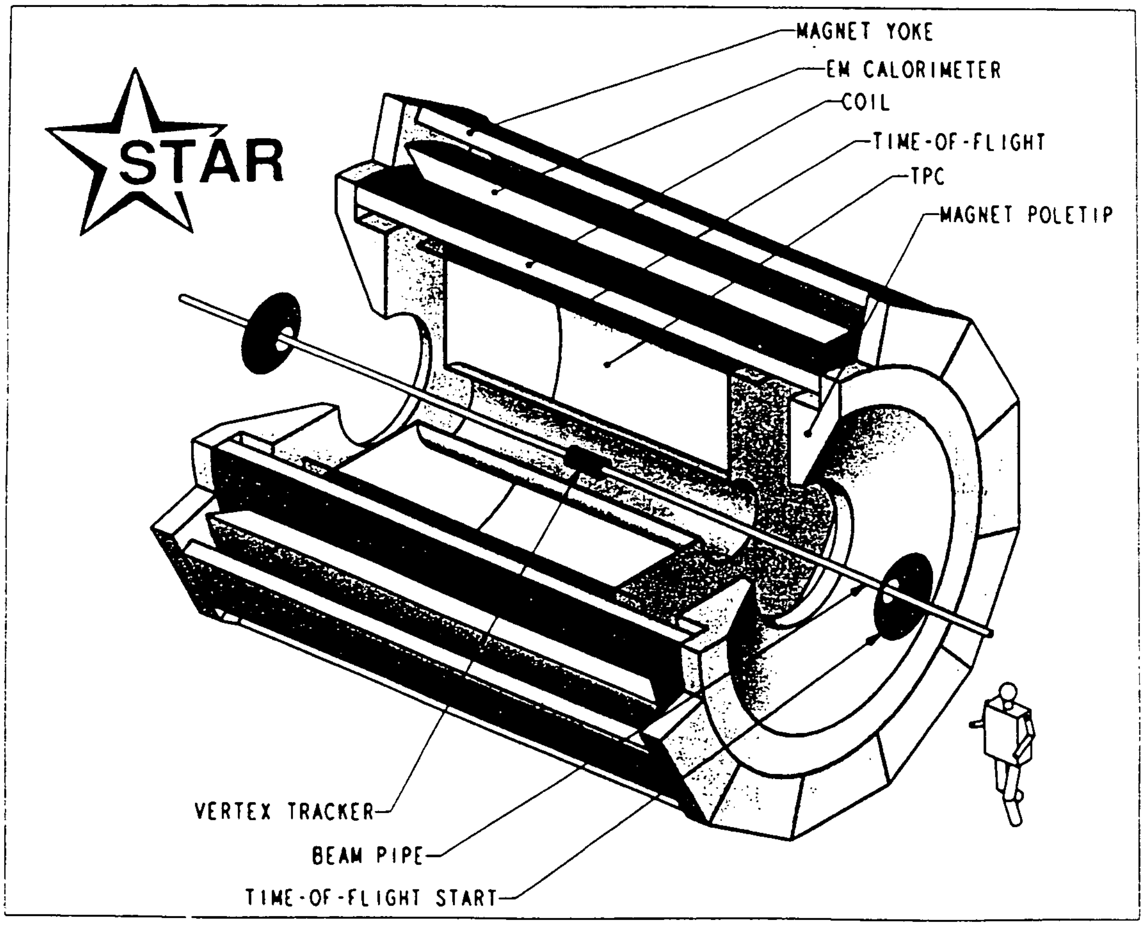

Fig. 1. Conceptual layout of the experiment, with cylindrical symmetry around the beam axis. See text for description.

2. Physics of STAR

2.1 Particle Spectra

As a consequence of the high multiplicities in central nucleus-nucleus events, the slope of the transverse momentum (p_t) distribution for pions and the $\langle p_t \rangle$ for pions and kaons can be determined *event-by-event*. Thus, individual events can be characterized by "temperature" to search for events with extremely high temperature, predicted[5] to result from deflagration of a QGP. Displayed in Fig. 2 are two spectra generated by the Monte Carlo method from Maxwell-Boltzmann distributions with T = 150 and 250 MeV, each containing 1000 pions. This is the average number of pions of a given charge sign expected in the acceptance $|\eta| < 1$ of this experiment for central Au + Au collisions. The slopes of spectra with T = 150 and 250 MeV derived from fits using a Maxwell-Boltzmann distribution, also shown in Fig. 2, can easily be discriminated at the single event level. The determination of $\langle p_t \rangle$ for pions can be made very accurately on the single event basis in this experiment, over the expected range of multiplicities in central collisions from Ca + Ca to Au + Au. Even for kaons, with ~ 200 charged kaons per event in the acceptance for central Au + Au events, $\langle p_t \rangle$ can be determined accurately for single events.

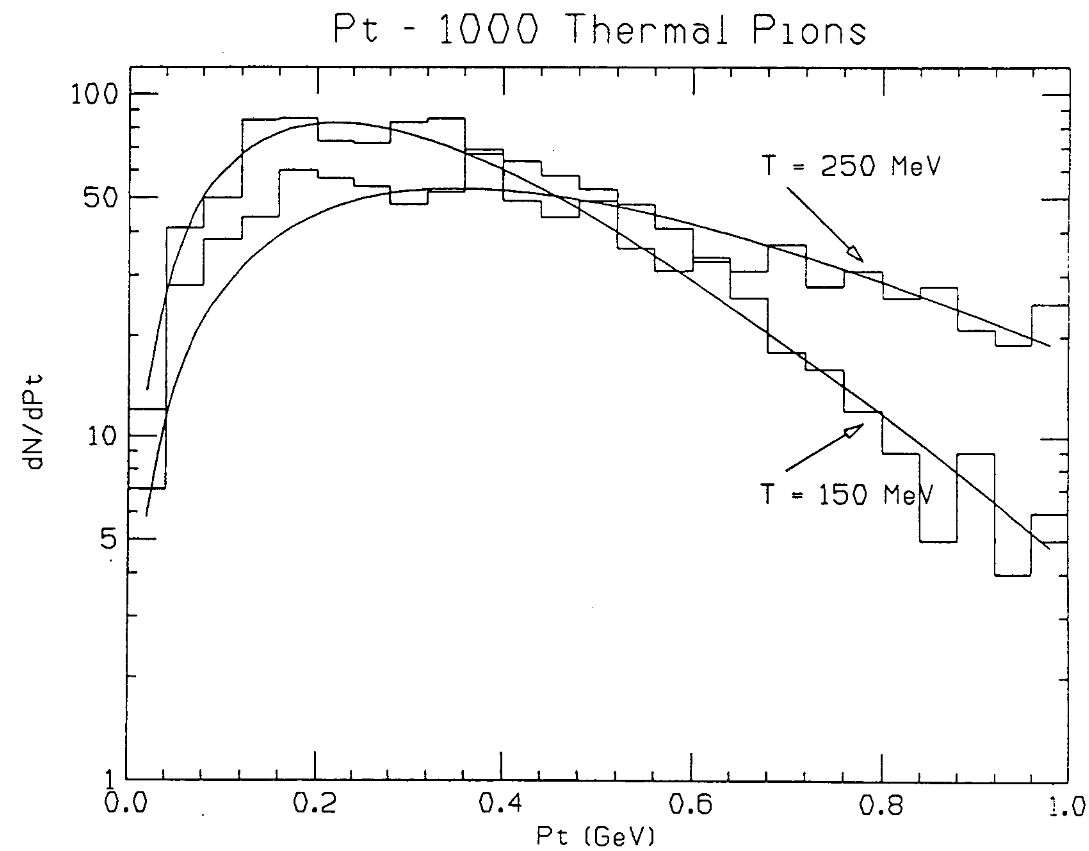

Fig. 2. Simulation of the p_t spectrum for one event generated using a Boltzmann distribution of 1000 pions. The histograms correspond to single events generated with T = 150 MeV and 250 MeV. The curves are fits to the histogram using a Maxwell-Boltzmann distribution (see text).

Inclusive p_t distributions of charged particles will be measured with high statistics and effects such as collective radial flow[6] and critical temperature[7] at low p_t, and mini-jet attenuation[8] at high p_t will be investigated. Since the central region of heavy ion collisions at RHIC is expected to have near-zero net baryon number, the p_t spectra of baryons and anti-baryons at midrapidity are particularly interesting for determining the stopping power of quarks. The difference between the p_t spectra obtained for p and $\bar{p}$ or Λ and $\bar{\Lambda}$ will reflect the redistribution in phase space of valence quarks from the nucleons of the target and projectile. This measurement of the net baryon number and net charge is important for establishing the baryo-chemical potential $\mu_B(y)$ at midrapidity.[9]

2.2 Strangeness Production

There have been many predictions regarding signatures of the QGP. One of the first predictions of a signature for the formation of a QGP was the enhancement in the production of strange particles resulting from chemical equilibrium of a system of quarks and gluons[10]. A measurement of the K/π ratio provides information on the relative concentration of strange and nonstrange quarks, i.e. $\langle(s + \bar{s})/(u + \bar{u} + d + \bar{d})\rangle$. This has been suggested[11] as a diagnostic tool to differentiate between a hadronic gas and a QGP, and to study the role of the expansion velocity. The K/π ratio will be measured *event-by-event* with sufficient accuracy to classify the events for correlations with other event observables. Another unique feature of STAR is its ability to measure strange and anti-strange baryons (e.g., Λ, $\bar{\Lambda}$) over a wide rapidity interval about midrapidity. Enhancements to the strange antibaryon content due to QGP formation have been predicted.[12] Furthermore, multiply-strange baryons (Ξ^-, Ω^-) may be more sensitive to the existence of the QGP.[13]

2.3 Hanbury-Brown and Twiss (HBT) Interferometry

Correlations between identical bosons provide information on the freezeout geometry,[14] the expansion dynamics[15] and possibly the existence of a QGP.[16] It would be interesting and unprecedented to be able to measure the pion source parameters via pion correlation analysis on an *event-by-event* basis and to correlate them with other event observables. In an individual event with 1000 negative pions within $|\eta| < 1$, the number of $\pi^-\pi^-$ pairs is $n_{\pi-}(n_{\pi-}-1)/2 = 500{,}000$. The two-pion correlation statistics for a single central Au + Au event at RHIC will be similar to the accumulated statistics published in most papers on the subject. An empirical relation for the transverse radius (R_t) of the pion source at midrapidity as a function of the rapidity density (dn/dy) has been derived from the existing pion correlation data[17] shown in Fig. 3. This relation, $R_t \sim (dn/dy)^{-1/3}$, suggests that rather large source sizes, $R_t \sim 10$ fm, will be measured in central Au + Au collisions at RHIC.

The correlations of like-sign charged kaons or pions will be measured on an *inclusive* basis to high accuracy. The dependence of the source parameters on the transverse momentum components of the particle pairs will be measured with high statistics. Measurement of correlations between unlike-sign pairs will yield information on the Coulomb corrections and effects of final state interactions. The *inclusive* measurement of KK correlations will complement the $\pi\pi$ correlation data. The KK correlation is less affected by resonance decays after hadronic freeze-out than the $\pi\pi$ correlations[18], thus interpretation of the KK correlation measurements is much less model-dependent than that of the $\pi\pi$ data. Since K's are expected to freeze out earlier[19] than π's in the expansion, the K source sizes are expected to be smaller than those of the π's. Depending upon the baryo-chemical potential and the existence of a QGP, the K^+ and K^- are also expected to freeze out at different times. Thus, separate measurements of the K^+K^+ and K^-K^- correlation functions will be of interest.

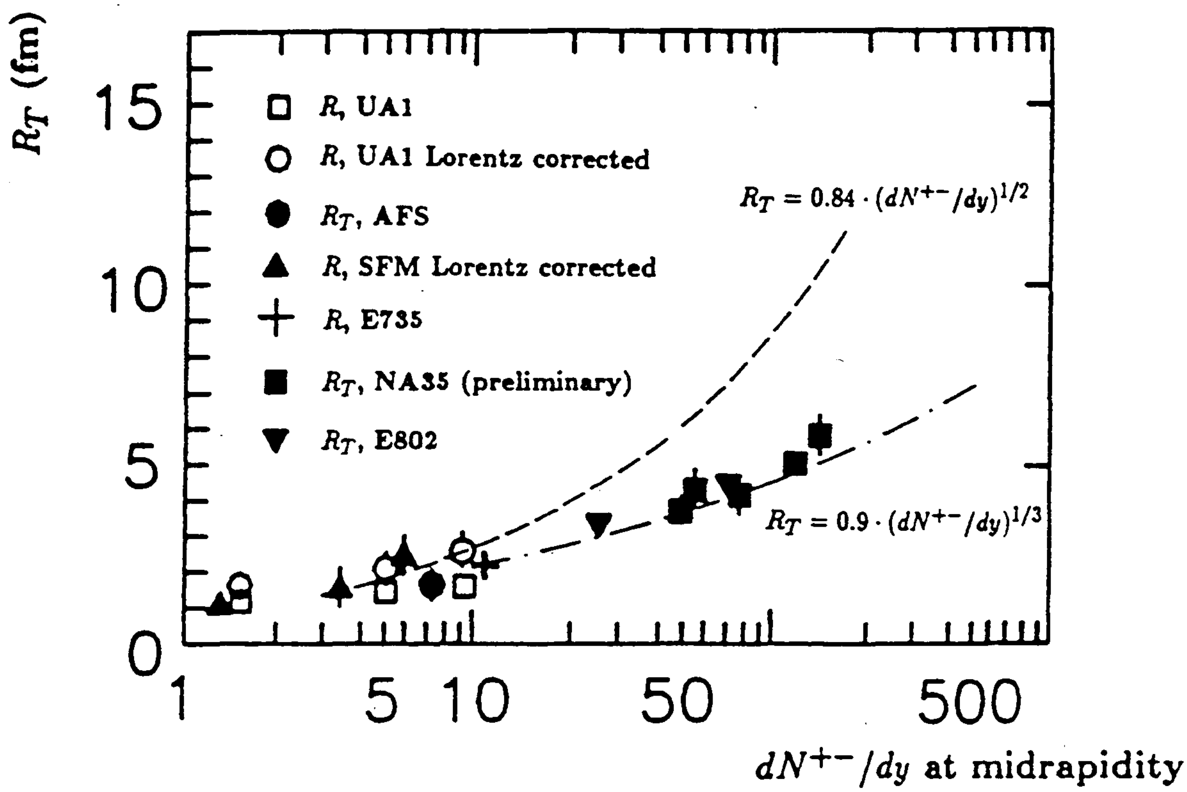

Fig. 3. The correlation between the transverse source radii, derived from two-pion correlation measurements, and the charged-particle rapidity density at midrapidity. Measurements from the Sp $\bar{p}$S collider, ISR collider, Tevatron collider, Brookhaven AGS heavy ions and the CERN SPS heavy ions are presented. Two parameterizations corresponding to $R_t \sim (dn/dy)^{-1/2}$ and $R_t \sim (dn/dy)^{-1/3}$ are shown.

2.4 Electromagnetic Energy

One-third of the energy produced at midrapidity in these collisions will be electromagnetic (EM) energy. The hadronic energy can be measured by charged particle tracking. The EM energy must be measured using calorimetry. The measurement of EM energy vs charged-particle energy is an important correlation to measure in the search for the QGP and other new physics. The unexplained imbalance between charged particle and neutral energy observed in Centauro and other cosmic ray events emphasizes the need for EM/charged particle measurements.[20] Discussions of quark-gluon scattering within the QGP (eg., $qg \rightarrow \gamma q$) also point to the importance of measuring the electromagnetic energy as a possible signature of special events.[21]

2.5 Fluctuations in Energy, Entropy, Multiplicity and Transverse Momentum

It has long been known that a prime, general indicator of a phase transition is the appearance of critical dynamical fluctuations in a narrow range of conditions. It is worth emphasizing that such critical fluctuations can only be seen in individual events where the statistics are large enough to overcome uncertainties ($\sqrt{N}$) due to finite particle number fluctuations. The large transverse energy and multiplicity densities at midrapidity in central collisions allow *event-by-event* measurement of fluctuations in particle ratios, energy density, entropy density and flow of different types of particles as a function of p_t, rapidity, and azimuthal angle. They also allow measurements of local fluctuations in the magnitude and azimuthal distribution of p_t. These fluctuations have been predicted to arise from the process of hadronization of a QGP.[22]

2.6 Parton Physics from Jets, Mini-Jets and High p_t Single Particles

The goal of studying products of hard QCD processes produced in relativistic heavy ion collisions is to use the propagation of quarks and gluons as a probe of nuclear matter, hot hadronic matter and quark matter. Since the hard scattering processes are directly calculable in QCD, a measurement of the yield of hard scattered partons as a function of their transverse energy should be sensitive to their interaction with the surrounding matter. The partons in a single hard scattering (dijet) whose products are observed at midrapidity must traverse distances of several fermi through high density matter in a nucleus-nucleus collision. The energy loss of these propagating quarks and gluons is predicted[23] to be sensitive to the medium and may be a direct method of observing the excitation of the medium, i.e., the QGP. Passage through hadronic or nuclear matter is predicted to result in an attenuation of the jet energy and broadening of jets. Relative to this damped case, a QGP is transparent and an enhanced yield is expected. The yield of jets will be measured as a function of the transverse energy of the jet. The jet events can also be correlated with other *event-by-event* observables to deduce information on the dynamics of the collision process.

Mini-jets are expected to be produced copiously in collisions at RHIC.[24,25] As is the case for high p_t jets, the observed yield of mini-jets is expected to be influenced strongly by the state of the high density medium through which they propagate. It is important to study the degree of fluctuation of the transverse energy and multiplicity as a function of rapidity and azimuthal angle ($d^2E_t/dyd\phi$ and $d^2n/dyd\phi$) *event-by-event*, which should be strongly affected by mini-jets.[26]. The *inclusive* p_t distributions of hadrons at $p_t > 3$ GeV/c will also be influenced by jets and mini-jets.

2.7 Correlations between Event Observables

It should be emphasized that the capability of measuring several different observables event-by-event is unique to this experiment. Events can be characterized event-by-event by their temperature, flavor content, transverse energy density, multiplicity density, entropy density, degree of fluctuations, occurrence of jets and possibly source size. The presence of a QGP is not likely to be observed in an average event, nor is it expected to be observed in a large fraction of events. Since there is no single clearly established signature of the QGP, access to many observables simultaneously will be critical for identifying the rare events in which a QGP is formed.

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